PRELIMINARY REPORT, PHASE II-III (12 MARCH 2015)

FUNDING AGENCY: Arctic Landscape Conservation Cooperative

PROJECT OFFICER: Phillip Martin, Arctic Landscape Conservation Cooperative, U.S. Fish and Wildlife Service, Fairbanks, AK

PROJECT TITLE AND ELEMENT: Evaluating the bottom-up effect of changing habitats: climate changes, vegetation changes, and the nutrient dynamics of ungulate forages

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BACKGROUND AND OBJECTIVES

Climate changes are affecting populations of northern ungulates through altering the abundance and phenology of vegetation in the Arctic (Martin et al. 2009). Increasing temperatures (>2°C) and shifts in hydrologic regimes have facilitated the conversion of tussock tundra to shrubs (Tape et al. 2006), increased the biomass of vegetation in the Arctic biome (Martin et al. 2009), and advanced the onset and extended the duration of the growing season (Goetz et al. 2005). For northern ungulates, the high seasonal variation in plant abundance and quality accentuates the need to replenish body stores during a short growing season that is critical for reproduction and winter survival (Cameron et al. 1993, Barboza and Hume 2006). Indeed, the predominant effects of climate changes to populations of northern herbivores are likely to be nutritionally mediated through vegetative changes (Klein et al. 2005).

Changes in the onset and duration of the growing season and vegetation productivity are affecting the timing of nutrient (i.e., energy and nitrogen) availability for northern ungulates (Lenart et al. 2002, Cebrian et al. 2008). The nutritional demands for energy and protein are highest for reproductive females during early lactation (White et al. 1989, Barboza and Parker 2008). For caribou (*Rangifer tarandus*), parturition generally occurs during the period of plant emergence or "green up", which allows females to offset the peak nutrient demands of lactation through the availability of highly digestible forages (White 1983, Barboza and Parker 2008). Emerging plants are an excellent source of digestible protein due to the limited structural and chemical defenses in growing tissues (Johnstone et al. 2002). As growth slows and plants mature, defensive tissues and compounds increase (Robbins et al. 1987a) with concomitant decreases in digestibility (Finstad 2008). Plant maturation coincides with peak forage production and increasing forage intake by large herbivores (White 1983). In Greenland, observations suggest that the onset of the growing season is occurring earlier while the timing of migration and parturition in caribou remains static. Thus, possibly creating a "mismatch" between peak nutrient availability and peak nutritional demands of lactating females and potentially affecting

productivity of this population (Post and Forchhammer 2008). However, peak nutrient intake is a product of forage availability, intake, and nutrient concentration and digestibility, so peak nutrient availability may not occur during plant emergence, but, rather, during the period of peak forage biomass (Griffith et al. 2010). Therefore, increases in vegetative productivity and extended growing seasons associated with warming (Martin et al. 2009), coupled with the ability of herbivores to forage selectively (White 1983) may result in substantial nutritional benefits for northern ungulates (Griffith et al. 2010). Although if vegetation biomass shifts from graminoid to shrub-dominated tundra (Martin et al. 2009), increases in shrub biomass may decrease the availability of nutrients to herbivores due to the increased ratio of lignified to green tissues and chemical defenses, or anti-nutrients, common in shrubs (Robbins et al. 1987a, Robbins et al. 1987b).

To elucidate these potential "bottom up" effects of climate changes to Arctic ungulates and evaluate the trophic mismatch hypothesis, the Arctic Landscape Conservation Cooperative (ALCC), the Bureau of Land Management (BLM), the U.S. Geological Survey (USGS), Teck, Inc., and the National Park Service provided funding in 2012-14 to incorporate the calving and summer range of the Western Arctic caribou herd (WAH) into an ongoing inter-agency research and monitoring effort to examine the influences of climate change on the nutrient dynamics of caribou forages. This work is leveraging existing projects on the North Slope of Alaska that are primarily funded through the USGS Changing Arctic Ecosystems Initiative. Field work on the spatio-temporal characteristics of summer habitats for the Teshekpuk (TCH) and Central Arctic (CAH) caribou herds commenced in May 2011 and terminated in September 2013; these efforts were fully funded through the USGS and the Alaska Department of Fish and Game (Fig. 1). Fieldwork in northwest Alaska commenced in May 2013 and terminated in October 2014. The north-south transect along the western boundary of the National Petroleum Reserve-Alaska (Fig. 1) 1) expanded the scope and inference of the caribou habitat monitoring efforts; 2) facilitated spatio-temporal comparisons of habitat characteristics among ranges of caribou; and 3) improved the empirical framework for bio-climate models that will help to evaluate the potential nutritional implications of a warming Arctic to important subsistence resources, such as caribou and other ungulate populations, throughout the North Slope. The **Objectives** for this project were to:

1) *Establish an environmental monitoring network in northwest Alaska;*
2) *Examine nutrient abundance and availability for caribou forages across spatial and temporal gradients;*
3) *Acquire, analyze, and summarize the historic and predicted climatic data for northwestern Alaska; and*
4) *Quantify the spatio-temporal availability of forage proteins of caribou throughout the growing season under the current and projected climatic regimes on the North Slope of Alaska*

ACTIVITIES AND STATUS

As part of an Interagency Agreement in 2012, the BLM provided $30,000 ($23,054 net project funds) to the USGS to address **Objective 1** and the Arctic LCC provided $300,000 ($199,575 net project funds) to address **Objectives 2-4**. These funds supported, in part, equipment and data fees for environmental monitoring stations ($29,365); helicopter-assisted fieldwork based out of Red Dog Mine in northwest Alaska in 2013 ($98,250) and 2014 ($88,360); travel ($5,400); technician position for 2014 ($14,100); costs of forage analyses ($24,000); and part-time support

for 2 graduate students ($32,000). In the original study plan, field work was to continue into 2015, however, due to realized costs of conducting helicopter-based fieldwork in northwest Alaska, field work ended in October 2014. Due to the stage of this project, this report details activities of **Objective 1 and 2**, but upon completion of remaining forage analyses from the 2014 field season, a final report will be completed and all data will be submitted and formatted as established either by the USGS Alaska Science Center protocols and (or) Alaska Data Integration Working Group.

REPORT

Objective 1: *Establish an environmental monitoring network in northwest Alaska*

Approach

Based out of Red Dog mine, we used a helicopter (R-44) to deploy 7 complete stations equipped with satellite-capable dataloggers, environmental sensors, as well as electric bear fences, 4-12 May, 2013. Stations (N-T) were deployed along a 144-km transect along the western boundary of the NPR-A within the Kokolik-Utukok drainages (Fig. 1); locations coincided with stations of habitat monitoring plots for the Western Arctic caribou herd. Stations were maintained, repaired, and (or) replaced as necessary until removal 1 Oct 2014.

Stations: Each station consisted of a 2-m aluminum tripod, a grounding rod, environmental sensors, a datalogger, 2 time lapse cameras, and an electric bear fence powered by solar charger (Table 1). With one leg of tripod oriented due south, the 3-piece tripod frame was staked directly to the ground with 30-cm steel spikes. Three guy lines (2.4 m each) were attached to the top portion of the tripod mast and were each anchored to a 46-cm piece of reinforced steel bar (1.3 cm in diameter) that was driven with a sledgehammer into a pre-drilled hole (1 cm) in frozen ground (Fig 3). Each tripod was grounded to a 1.2-m copper grounding rod that was driven into the frozen ground at 30-45 cm. Tripods were adjusted as necessary to provide a level and stable structure to attach dataloggers and sensors.

The solar powered satellite-capable dataloggers were attached with u-bolts and grounded to the south-facing tripod leg (Fig. 2). The loggers recorded and transmitted data daily via the iridium satellite network and the data are stored in a secure online database managed by DataGarrison (https://datagarrison.com/). Data are accessible with a user id and a password (D. Gustine can provide these as necessary). Loggers transmitted data as long as onboard batteries were above a maintenance charge (~30%), so as days grow shorter and battery charge declines, transmission functions were shut off but the loggers were still storing data. Transmission resumed when batteries are fully charged, which was typically sometime in March.

Satellite-capable dataloggers acquired and initially transmitted data for 6 sensors. Sensors were connected directly to the logger through category 5 cables. Sensors were monitoring hourly measurements of wind speed, air temperature, and light (Table 1). Wind and air temperature required one sensor port each, while light required 4 ports. To provide data security for air temperature data as well as log soil temperature, we deployed 2 pendant dataloggers to collect additional hourly air temperature as well as record soil temperature at 10-12 cm. These pendant loggers were used to collect similar data along the TCH and CAH

transects (Fig. 1) in the growing seasons of 2011-13. Both air temperature sensors/loggers were housed in solar radiation shields to insure accurate measurements of air temperature (Fig. 2). Unlike the satellite datalogger, pendant loggers were physically collected from the field to download the stored data. The 4 light sensors were used to calculate NDVI.

Time-lapse photography was used to acquire a near continuous record of environmental conditions and animal phenology (Tape and Gustine 2014) in 2014. Plot Stalker cameras (Moultrie, Lafayette, LA) with 16 GB memory cards and powered by 4 lithium AA batteries were mounted on wooden plank attached to the grounding rod of each station (Fig. 3). Directions and angles of cameras were adjusted at each macroplot to maximize the area recorded by the camera. Digital photos were taken at 15-minute intervals throughout the sampling period.

To minimize loss of, or damage to, these stations from ursids, each station was surrounded by electrified fence (Fig 2). The footprint of the fence was a pentagon centered on the station with approximately 2.5-3.0 m sides. The fiberglass fence posts were 1.5 m long and were tapped into holes that were drilled in frozen ground. Four fence lines (poly twine interwoven with 9-strands of stainless steel wire) were strung every 15-30 cm with the bottom line at least 30 cm above the ground and surrounding vegetation. The fence was charged with a solar-powered weather proof energizer that charged the fence with 9,900 volts (0.5 joule; Table 1). The charger was faced south and mounted on the top of a steel fence post (Fig. 2) that was set into frozen ground with a hammer drill and a sledgehammer. The charger was grounded to either the steel post or a guy stake for the tripod. Two of the 4 fence lines were grounded to the charger while the remaining 2 lines were electrified. Grounded and electrified lines were alternated (Fig. 2) to insure that any animal that came into contact with the fence was properly grounded and, thus, would receive the bulk of the 9,900 volts from the fence. Voltage of each fence was tested with a fence tester, while the efficacy of the fence was tested, often inadvertently, at least once by each member of the field crew. As the growing season progressed, vegetation was removed from the fence line as necessary – vegetation could reduce the electrical load of the fence and, thus, may be inadequate to deter a grizzly bear.

Deployment: The field crew was based out of Red Dog Mine (Teck, Inc.) on the southwest side of the Brooks Range in northwestern Alaska. Red Dog Mine is approximately 60 miles southwest of the southernmost habitat monitoring plot. Teck, Inc. shipped the weather stations and equipment (~230 kg) from Anchorage to Red Dog on Northern Air Cargo. Teck, Inc. provided all travel to and from Red Dog Mine on the Alaska Airlines chartered flight to and from Anchorage, AK; food and lodging at Red Dog Mine; as well as sold helicopter fuel to the project at their cost (~$8/gallon). Crew and helicopter pilot arrived at Red Dog on May 4, 2013, but due to a blizzard, we did not deploy the stations until May 9-10. With the crew, equipment, and fuel, the helicopter could carry 4 complete stations. It took 2 full days to set up 7 stations, but if the snow had been shallower (Fig. 2) or the stations were deployed in late summer-fall, it probably could have been done in one long day.

Preliminary data

Cumulative thaw degree days from CAH, TCH, and WAH transects 2011-14: As an index of growing conditions for plants, temperature data from all monitoring plots (A-T; Fig. 1) were converted to thaw degree days (TDD). Thaw degree days is the degrees above 0°C for a Julian date with an average temperature > 0°C. Cumulative TDDs were the sum of TDD up to a Julian date of each growing season. Average cumulative TDDs were reported by herd, ecoregion, and year over the day of the year (140-280).

The Coastal Plain was always cooler (cumulative TDDs = 670-960) than the Arctic Foothills (910-1240) and Brooks Range (900-1210) throughout the growing seasons of 2011-13 (Fig. 5). The Coastal Plain, where the CAH and TCH typically calve, did not substantially warm until after calving (Fig. 5), while the Arctic Foothills (75), where the WAH calved, was 120% warmer than the Coastal Plain (34) in northwest Alaska.

Time-lapse photography of WAH stations 2014: Courtesy of Lauren Salberg's substantial effort as well as methodology described in Tape and Gustine (2014), time-lapse cameras along the WAH transect acquired approximately 42,000 images with a total of 5,748 observations of caribou (Fig. 6). Additionally, videos of the time-lapse series for each environmental station were produced by Keith Oster at UAF. An example from station P (Fig. 1) has been included in an email with this report to Phillip Martin with the Arctic LCC.

Status and Performance

After inquiring with the Arctic LCC, the BLM, and F. Urban with the USGS in July-August 2014 as to whether to remove or leave the stations in the field, we attempted to retrieve stations in October 2014. Due to weather, time, and aviation costs, we could only remove electronic equipment (sensors, dataloggers, and time-lapse cameras) from the 5 southern sites. Thus, the 2 northern sites remain active while the tripods, bear fences, grounding rods remain in the field for the 5 southern sites – we will attempt to fully remove the stations in the summers of 2015-16.

It was difficult to evaluate the capacity of the stations to endure the often austere environmental conditions in the Arctic. Despite our best efforts to deter grizzly bears with a high-voltage electric fence, bears completely or partially damaged 6 of 7 stations in 2013 and partially damaged 3 of 7 stations 2014 (Table 2). The lone exception was the far north site (7) about 32 km east of Point Lay (Fig. 2). Three of 6 stations were damaged by bears on multiple occasions in 2013 and 2014 (Table 2). It is unclear how successful our fences were in deterring bears, as we could not record incidents of "successful" deterrence, however, we suspect that the damage from bears would have been greater without the fences. The Kokolik-Utukok uplands have some of, if not the, highest densities of grizzly bears (*Ursus arctos*) on the North Slope (H. Reynolds, pers. comm.). Future efforts by our group as well as other planned activities (e.g., Terrestrial Ecosystem Observation Network), should consider that regardless of their best efforts, expensive equipment will be prone to being repeatedly damaged or destroyed. Another incidence of damage, albeit a rare one, was due to a lightning-caused tundra fire (311 Archimedes Fire, 6/20/2013, 600 ha) that partially damaged station P. Outside of these "natural" occurrences, satellite-capable dataloggers were simple to deploy and appeared to work well. Unfortunately due to the damage frequently incurred by these stations, wind and light sensor data have poor to no temporal

coverage. However, due to the second air temperature pendant loggers that were deployed for each station in northwest Alaska, we have complete spatial and temporal coverage of hourly temperatures for the growing seasons of 2013-14 as well as similar temperature data for 2011-13 for the CAH and TCH transects (Fig. 1).

Considerations for deploying and maintaining an environmental monitoring network
Despite the clear need and utility of an environmental monitoring network in the western NPRA, there are some clear challenges to maintaining a permanent monitoring presence in the area. Cost for the hardware for the station, not including shipping, was $3,845/station (Table 1). If stations can indeed be deployed by helicopter in 2 days of flying from Red Dog, that's about $10,500 in ferry time, fuel, and flight time, or an additional $1,500/station for a total cost of $5,345/station with additional Iridium fees of $350/station/year. The stations need to be occasionally accessed for maintenance (e.g., adjust fencing and guy lines due to frost heaving, replace frozen batteries, etc), so the cost/station will increase. However, if an agency or research group is spending additional resources on replacing stations *multiple times* a year, maintaining a network with a high upfront cost may not be financially possible. Bears happen − so any monitoring effort in the Kokolik-Utukok uplands should include this into the cost of deployment and management of a network. Alternatively, each station could be heavily defended by large plastic structures; this is common for GPS-seismic monitoring stations.

Objective 2: *Examine nutrient abundance and availability for caribou forages across spatial and temporal gradients*

Approach
Soil and vegetation characteristics were monitored at 20 macroplots in 3 ecoregions (Coastal Plain, Arctic Foothills, and Brooks Range) from May-September on the North Slope of Alaska (Fig. 1) in 2011-2014. Macroplots (0.05 km^2) were positioned to minimize the effects of topography (Nellemann and Thomsen 1994); encompass the representative vegetation of the area (Williams and Rastetter 1999); minimize the proportion of the macroplot that was covered by permanent water bodies; and (or) include historic sampling locations (A-I; Whitten and Cameron 1980). Macroplots were divided into 5 100 x 100-m quadrats. A grid of potential sampling points was established at 10-m intervals within the macroplot in a geographic information system (GIS; ArcGIS 10, ESRI, Redlands, CA). For each sampling period, a random sample without replacement of 5 locations was stratified among quadrats. Sampling plots (0.25 m^2) were located with a global positioning system (GPS) unit (Juno SD, Trimble, Sunnyvale, CA). Coordinates, general vegetation, temperature, relative humidity (Oakton Instruments, Vernon Hills, IL), and the presence, depth, and condition of snow and water were noted or measured prior to assessing abiotic and biotic characteristics for each plot.

Soil characteristics*:* We measured thaw depth for each sampling period. Sampling plots were delineated by collapsible frame made of polyvinyl chloride (PVC) tubing (0.25 m^2). Thaw depth (Auerbach et al. 1997) was measured at the center of the plot with a steel probe (1-m long, 1.27 cm diameter; ER-AS481/2F, Blacksmith Company, Monroe, NY).

The nutrient content of soil will be estimated at one sampling period in late summer (22-27 July; Table 3). Soils from the upper 10 cm of the organic horizon from the 5 plots in each macroplot were collected with a soil corer (7 cm in diameter, AMS Sampling, American Falls, ID; Kielland 1995), placed in a zip-top plastic bag, kept cool in the field, and then frozen until processing. In 2015, soils will be oven-dried (40°C), sieved (2 mm), sub-sampled (15 g), and assayed for pH, C (%), N (%), and S (%) as well as total Cu, Zn, Fe, Mo, NH_4-N, and NO_3-N in ppm.

Vegetation characteristics: Phenology, biomass, nutrient composition and availability (quality), and browsing intensity of vegetation was measured at 5 plots within each macroplot for each sampling period. Phenology (Cebrian et al. 2008) was recorded for 7 primary forages (i.e., *Eriophorum vaginatum*, *Carex aquatilis* and *bigewloii*, *Pedicularis langsdorfii*, *Salix pulchra, Salix richardsonii,* and *Betula nana*) within each plot. For deciduous shrubs, we measured height, noted evidence of browsing, and calculated browsing class (McArt et al. 2009).

Aboveground biomass of vascular vegetation (biomass) was collected for primary forages (see above) and functional groups (graminoids, forbs, and deciduous shrubs). Biomass of current annual growth ($g \cdot m^{-2}$) was directly measured by removal of vascular plant tissues at the 5 0.25 × 0.25 m plots in a macroplot. For each sample period, live (green) tissues were collected by forage species and functional group into paper bags and labeled with an indelible marker. Herbaceous plants were clipped (Felco Model 11, Kirkland, WA) or pulled at the surface of the ground, water, or moss; only the leaves of shrubs were collected. Due to the small size and often staggering abundance of horsetail (*Equisetum* spp.), these species were collected in one random quadrant (0.125 × 0.125 m) of the plot. Forage species typically did not occur in sufficient quantities for nutritional analyses within each plot, therefore, forage quality samples were collected adjacent to the macroplot. Samples were stored in paper bags in dry locations with constant air flow until processing. To assess total phenol concentration and protein-precipitating capacity, small sub-samples of shrubs (approx. 5 g) were transferred to plastic-zip top bags and frozen until processing. Upon return from the field, samples were dried in a forced-air oven at 40°C to constant mass (Servello et al. 2005). Dried samples were weighed to the nearest 0.0001 g in each paper bag. Samples for functional groups were transferred to vacuum-sealed bags for archiving. Samples for each forage species were transferred to plastic storage bags, while sub-samples of shrubs assayed for phenols and protein-precipitating capacity were lyophilized.

Forage quality was determined for each forage species for a macroplot by quantifying nutrient content and availability. Sample preparation and nutrient analyses occurred the winter after collection. Samples were ground through a 1-mm screen in a Wiley mill (Arthur Thompson Company, Philadelphia, PA). Analysis of nutrient composition (i.e., analytical dry matter, ash, proximate analyses, carbon and nitrogen content, gross energy, and macro- and trace mineral content) were as in Peltier et al. (2003). For the shrubs, phenol concentration and protein-precipitating capacity were determined as in McArt et al. (2006).

We assessed digestibility of N, energy, and minerals by an *in vitro* method using purified cellulase and pepsin that has been validated by *in sacco* digestion in the rumen of fistulated

reindeer followed by treatment with acid-pepsin (VanSomeren et al. 2015). Dry residues from the digestions were used to estimate dry matter digestibility in the rumen. The dried residues from the acid digestion were used to estimate digestibility in the whole digestive tract. The dried residues were assayed for ash, fiber fractions, gross energy, N, C, and macro- and trace minerals.

Preliminary data

Habitat measurements and forage collection for the CAH and TCH transects was completed in 2013, while WAH was completed in 2014. Soil, digestibility, phenol, mineral, and proximate assays are pending, thus we report the biomass and N and C abundance in forages by ecoregion and herd. Forage biomass ($g \cdot m^{-2}$) is the total biomass of the forage species (*Eriophorum vaginatum*, *Carex aquatilis* and *bigewloii*, *Pedicularis langsdorfii*, *Salix pulchra, Salix richardsonii,* and *Betula nana*) found on an average sampling plot within a macroplot. Forage N abundance ($g\ N \cdot m^{-2}$) is the N content (%) of a forage species multiplied by its biomass and summed across forage species, while forage C abundance ($g\ C \cdot m^{-2}$) is C content (%) of a forage species multiplied by its biomass and summed across forage species; both characteristics are presented as average estimates for a macroplot. Forage biomass, N, and C are presented as quadratic functions by ecoregion and herd on day of the year and cumulative TDD. Estimates of peak parturition (early June: days of year = 152−158; Cameron et al. 1993, Lenart 2011) and lactation (3 weeks after peak parturition: 173−179; Parker *et al.* 1990) were presented alongside forage characteristics to provide important context relative to reproductive phenology. For simplicity, model complexities and estimates of uncertainty were not provided in this preliminary report but will be in the final report.

Forage biomass at CAH, TCH, and WAH transects 2011-14: Emergent forage was typically not available for calving caribou in the CAH and TCH as they calved in the Coastal Plain, while the WAH generally calved in the Arctic Foothills. Forage biomass typically peaked earlier in the Arctic Foothills and Brooks Range (202-209) than in the Coastal Plain DOY (205-219) with higher forage productivity along the WAH transect (Fig. 7). Relative to cumulative TDDs, temperature thresholds to initiate growth of forage were typically lower in the Arctic Foothills (Fig. 8) and this was due, in part, to the large proportion of forage biomass that was *E. vaginatum* as this forage is commonly becomes available before the snowpack disappears. Temperature thresholds for peak biomass were approximately 570-670 in the Coastal Plain, 560-840 in the Arctic Foothills, and 570-660 in the Brooks Range (Fig. 8).

Forage N at CAH, TCH, and WAH transects 2011-14: Forage N increased rapidly throughout lactation and typically peaked earlier in the Arctic Foothills and Brooks Range (199-203) than in the Coastal Plain DOY (203-212) with higher forage N along the WAH transect (Fig. 7). Relative to cumulative TDDs, temperature thresholds for peak N preceded peak forage biomass and were approximately 450-465 in the Coastal Plain, 500-700 in the Arctic Foothills, and 550-575 in the Brooks Range (Fig. 8).

Forage C at CAH, TCH, and WAH transects 2011-14: Forage C increased rapidly throughout lactation and typically peaked earlier in the Arctic Foothills and Brooks Range

(200-210) than in the Coastal Plain DOY (207-222) with higher forage C along the WAH transect (Fig. 7). Relative to cumulative TDDs, temperature thresholds for peak C preceded peak forage biomass in the Coastal Plain (approx. 500), yet aligned with forage biomass in the Arctic Foothills (570-860) and in the Brooks Range (550-575; Fig. 8).

GRADUATE STUDENTS

Funding for this project has, in part, supported 2 graduate students at UAF:

1) Lindsay VanSomeren, M.S. (2012-2014); Thesis: Monitoring energy and nitrogen availability for Arctic caribou

2) Keith Oster, M.S. student (2014-2016); Thesis: Mineral dynamics in forages of migratory tundra caribou

CURRENT AND EXPECTED PRODUCTS

These habitat and temperature relationships and are being coupled with historic weather data and future climate scenarios to retrospectively (1975-2013) and prospectively (2010-2065) examine the potential climate-induced shifts in habitat quality for caribou in the Arctic. Copies of manuscripts listed below will provided by D. Gustine as requested.

VanSomeren, L., P. Barboza, D. Thompson, and D. Gustine. 2015. Monitoring digestibility of forages for herbivores: a new application for an old approach. Canadian Journal of Zoology: *in press*.

Gustine, D. D., P. Barboza, L. Parrett, and L. Adams. Foraging in seasonal windows: balancing nutrients, temperature, and insects for Arctic caribou 1975-2013. *In preparation*. Proceedings of National Academy of Sciences.

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VanSomeren, L., P. Barboza, D. Gustine, and M. S. Bret-Harte. Assessing nutrient availability for arctic caribou: interactions among nutrients, anti-nutrients, and stable isotope ratios. *In review*. Functional Ecology.

Gustine, D. D., P. Barboza, L. Adams, B. Griffith, R. Cameron, and K. Whitten. *In review*. Evaluating the evidence for a trophic mismatch for caribou in the Alaskan Arctic. Journal of Applied Ecology.

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VanSomeren, L., P. Barboza, and D. Gustine. 2014. An in vitro method for monitoring digestibility of forages for caribou. The 15th North American Caribou Workshop, Whitehorse, YT.

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Table 1. Components of, and cost to construct, an environmental monitoring station that was deployed in the Kokolik-Utukok Uplands, NPRA, May, 2013.

Component	Environmental characteristic (units)	Manufacturer and item	Item number	Cost/station
Tripod and sensor supports	*All*	Onset; complete 2-m tripod kit	M-TPB-KIT	180
	Wind	Onset; full cross arm kit	M-CAA	62
	Light	Onset; NDVI light sensor bracket	M-NDVI	17
	Light	Onset; light sensor bracket	M-LBB	128
Sensors	*Air temperature (°C)*	Onset; smart temperature sensor 12-bit w/ 2-m cable	S-TMB-M002	90
	Air temperature	Onset; solar radiation shield (12-bit)	RS3	59
	Air and soil temperature (°C)	Onset; pendant temperature/light sensor and logger	64K-UA-002-64	59
	Air temperature	Onset; solar radiation shield (pendant)	RS-1	79
	Wind (m/s)	Onset; wind Speed Smart Sensor with 3-m cable Sensor	S-WSA-M003	227
	Light (w/m^2)	Onset; silicon pyranometer sensor w/ 3-m cable (2/station)	S-LIB-M003	398
	Light (uE)	Onset; PAR sensor w/ 3-m cable (2/station)	S-LIA-M003	418
Dataloggers	*All*	Upward Innovations datalogger	DataGarrison - Solarstream Satellite Iridium	1,379
		Upward Innovations; fee to initialize station	n/a	50
		Upward Innovations; annual fee for Iridium service	n/a	360
Cameras	*Growing season*	2 Plot Stalker cameras, 16 G memory cards, and lithium batteries (AA)	Moultrie	120
Bear fence	*N/a*	Stafix; solar charger with 12-v battery	EXS.5	290
		Kencove; electric twine 9SS (55 m/station)	R49GO	5
		Sunguard; 1.5 m x 1.27 cm fiberglass fence posts (5/station)	F12-4SG	13
		Kencove; fence flags (5/station)	MFF	3
		Kencove; triple jumper leads (2/station)	MPC3	20
		Home Depot; 1.5 m steel T-fence post		8

Table 2. Metadata and status of environmental monitoring stations at caribou habitat plots (Fig. 1) on the North Slope of Alaska, 2011-14

Stations/plots	Latitude	Longitude	Elevation (m)	Status	Notes
A	68.649793	-149.365348	845.8	Inactive	
B	68.709860	-149.013655	650.0	Inactive	Will be re-deployed in April 2015 and active through June 2019 as part of Changing Arctic Ecosystems (CAE) research
C	69.062347	-148.799661	382.2	Inactive	
D	69.210604	-148.809454	286.1	Inactive	Will be re-deployed in April 2015 and active through June 2019 as part of CAE research
E	69.449056	-148.573408	185.2	Inactive	
F	69.660999	-148.687395	121.8	Inactive	
G	69.900898	-148.769373	70.3	Inactive	Will be re-deployed in April 2015 and active through June 2019 as part of CAE research
H	70.116255	-148.495241	25.8	Inactive	
I	70.354567	-148.618231	9.2	Inactive	
J	69.388197	-152.160408	0.9	Active	Temperature data from F. Urban (USGS-UAF; Umiat)
K	70.007095	-153.046517	32.9	Active	Temperature data from F. Urban (USGS-UAF; Inigok and WS2)
L	70.348153	-153.188231	54.3	Active	Temperature data from F. Urban (USGS-UAF; WS3) and ADFG
M	70.912662	-153.215222	120.7	Active	Temperature data from F. Urban (USGS-UAF; E. Tesh) and L. Parrett (ADFG)
N	68.665000	-161.569450	286.8	Inactive	Attacked by **bear** in early June 2013, then repaired; totally destroyed by **bear** in late Sep 2013; repaired in May 2014, attacked by **bear** and repaired in June 2014; sensors, data logger, and cameras were removed October 2014 but tripod and bear fence remain
O	68.887933	-161.361100	418.4	Inactive	Light sensors destroyed by **bear** in late Sep 2013; partially damaged by **bear** and repaired in June 2014; sensors, data logger, and cameras were removed October 2014 but tripod and bear fence remain
P	69.052650	-161.592517	316.3	Inactive	Partially damaged by **bear** in early June 2013, repaired; partially damaged by **fire** in late June 2013, repaired; sensors, data logger, and cameras were removed October 2014 but tripod and bear fence remain
Q	69.194183	-161.750617	185.9	Inactive	Totally destroyed by **bear** in late Sep 2013; repaired in May 2014; sensors, data logger, and cameras were removed October 2014 but tripod and bear fence remain
R	69.447317	-161.813000	105.4	Inactive	Wind and temperature sensors destroyed by **bear** in early November 2013; partially repaired in May 2014; sensors, data logger, and cameras removed October 2014 but tripod and bear fence remain
S	69.692950	-161.709217	57.5	Active	Wind sensor destroyed by **bear** in late September 2013; camera mounting post broken by **bear** in early June 2014 and repaired
T	69.958717	-161.661067	44.9	Active	

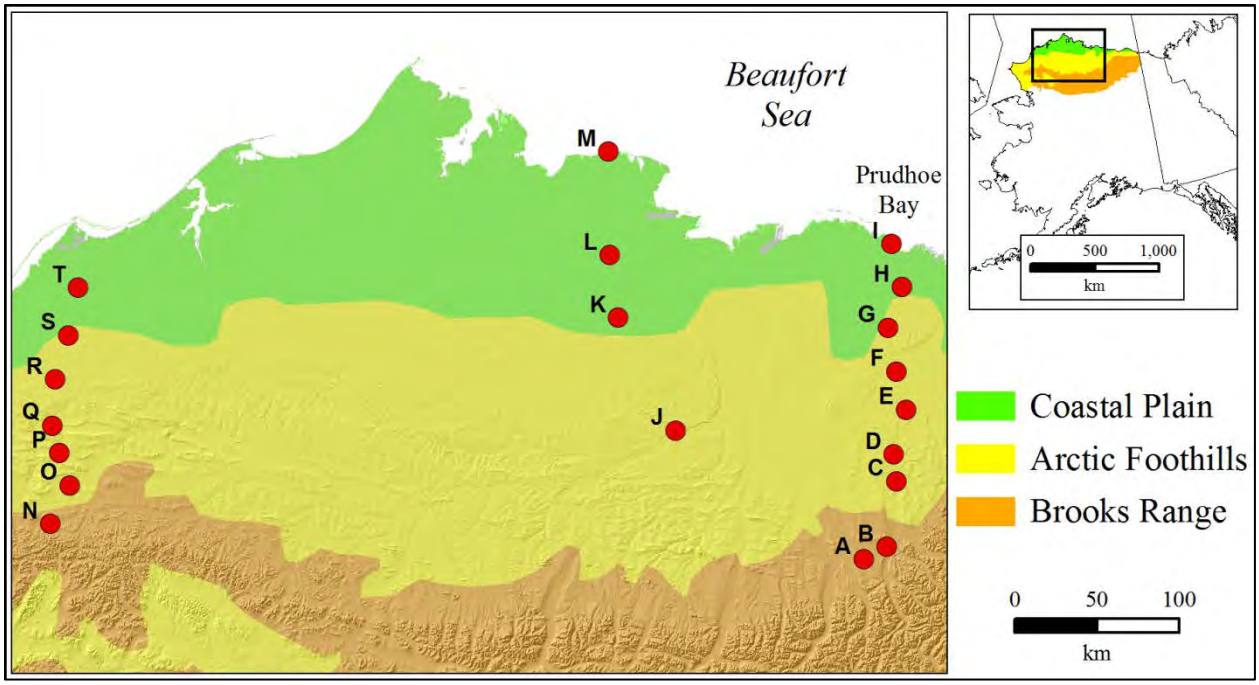

Figure 1. Plots to monitor the environmental conditions and the phenology, nutrient dynamics, and productivity of forages within the summer ranges of the Central Arctic (A-I), Teshekpuk (J-M), and Western Arctic (N-T) caribou herds on the North Slope, Alaska 2011-15.

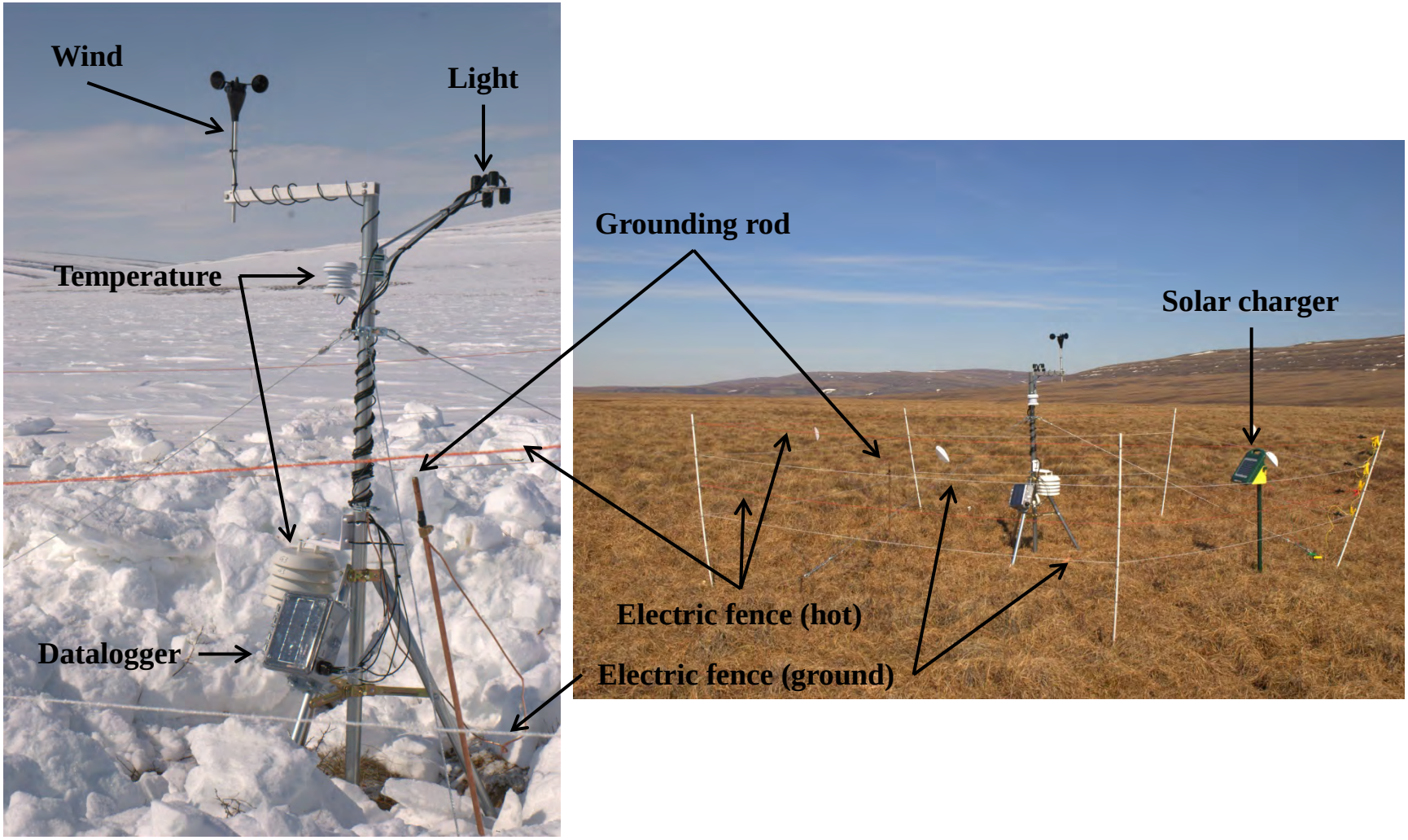

Figure 2. Configuration of environmental monitoring stations in northwest Alaska, 2013-14.

Figure 3. Time-lapse cameras deployed at environmental monitoring stations in northwest Alaska, 14.

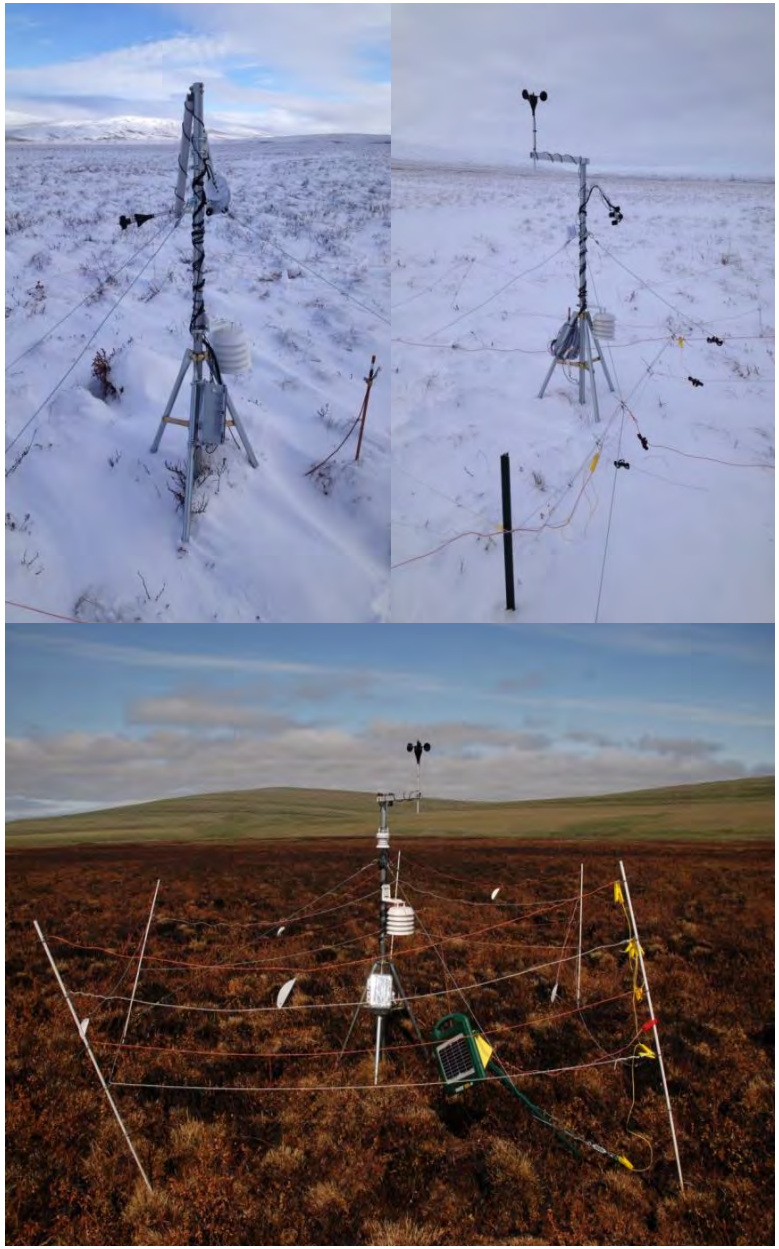

Figure 4. Examples of stations completely destroyed by grizzly bears in late September (top left panels) and partially damaged by lightning-caused fire in late June (bottom left panel), northwest Alaska, 2013 as well as a grizzly bear recorded by time-lapse photography in late May, 2014 (top right panel).

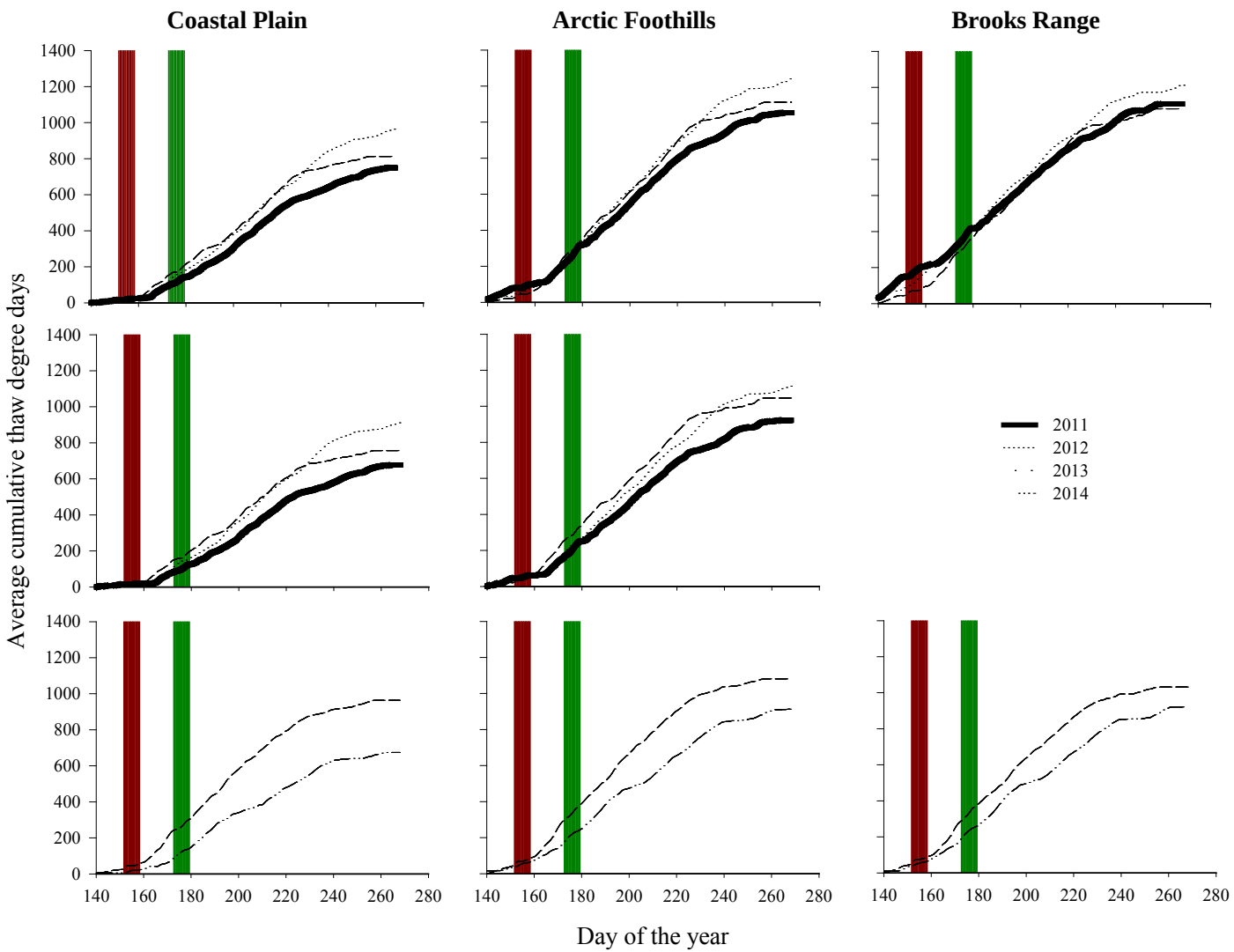

Figure 5. The average cumulative thaw degree days estimated from environmental monitoring stations at macroplots within each ecoregion (Fig. 1) for the Central Arctic (top row), Teshekpuk (middle row), and Western Arctic (bottom row) caribou herds on the North Slope of Alaska, 2011-14; peak calving and lactation are depicted by red and green bars, respectively.

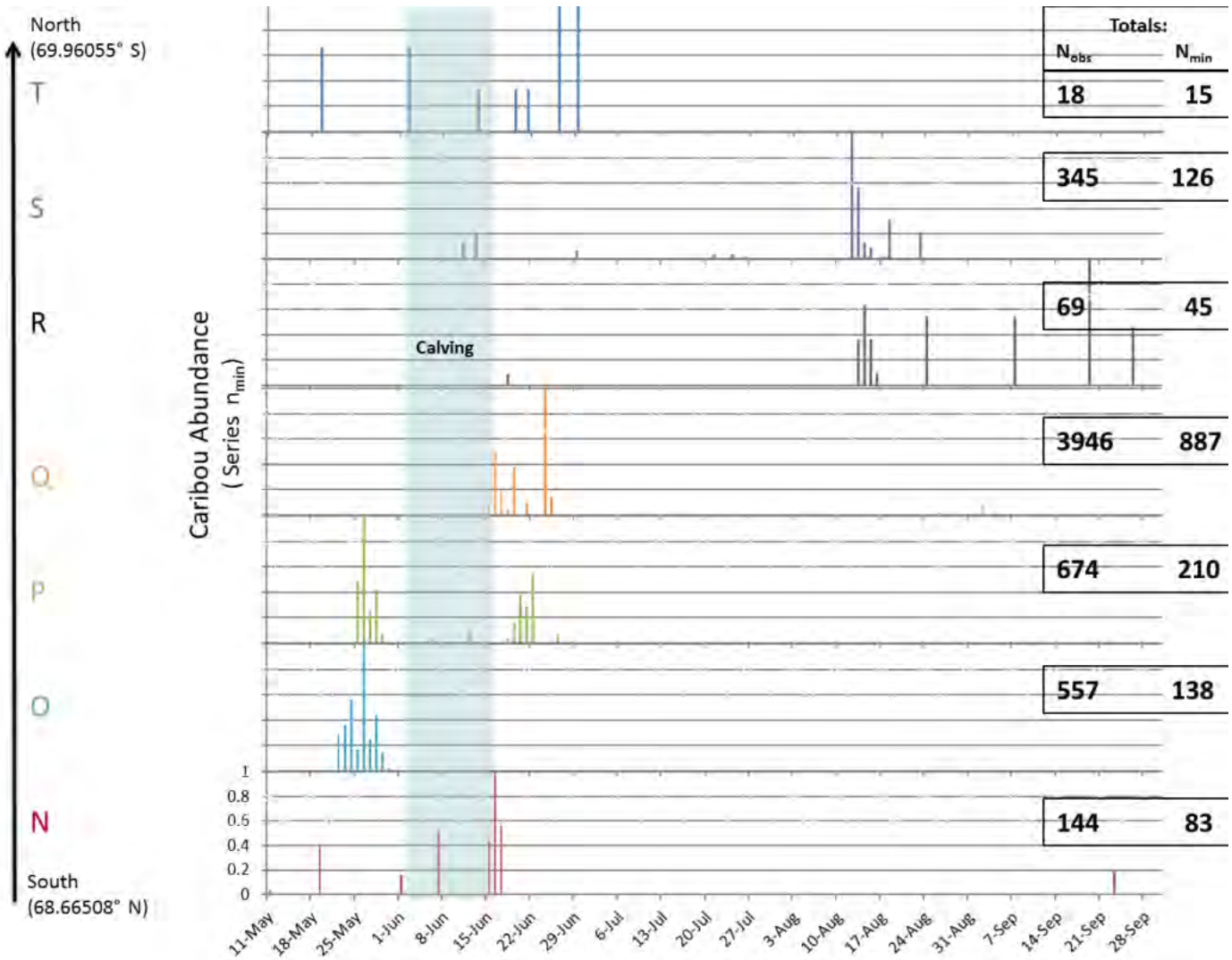

Figure 6. The proportion of caribou counted on time-lapse photos (Tape and Gustine 2014) at environmental monitoring stations (N-T; Fig. 1) by date in northwest Alaska, 2014.

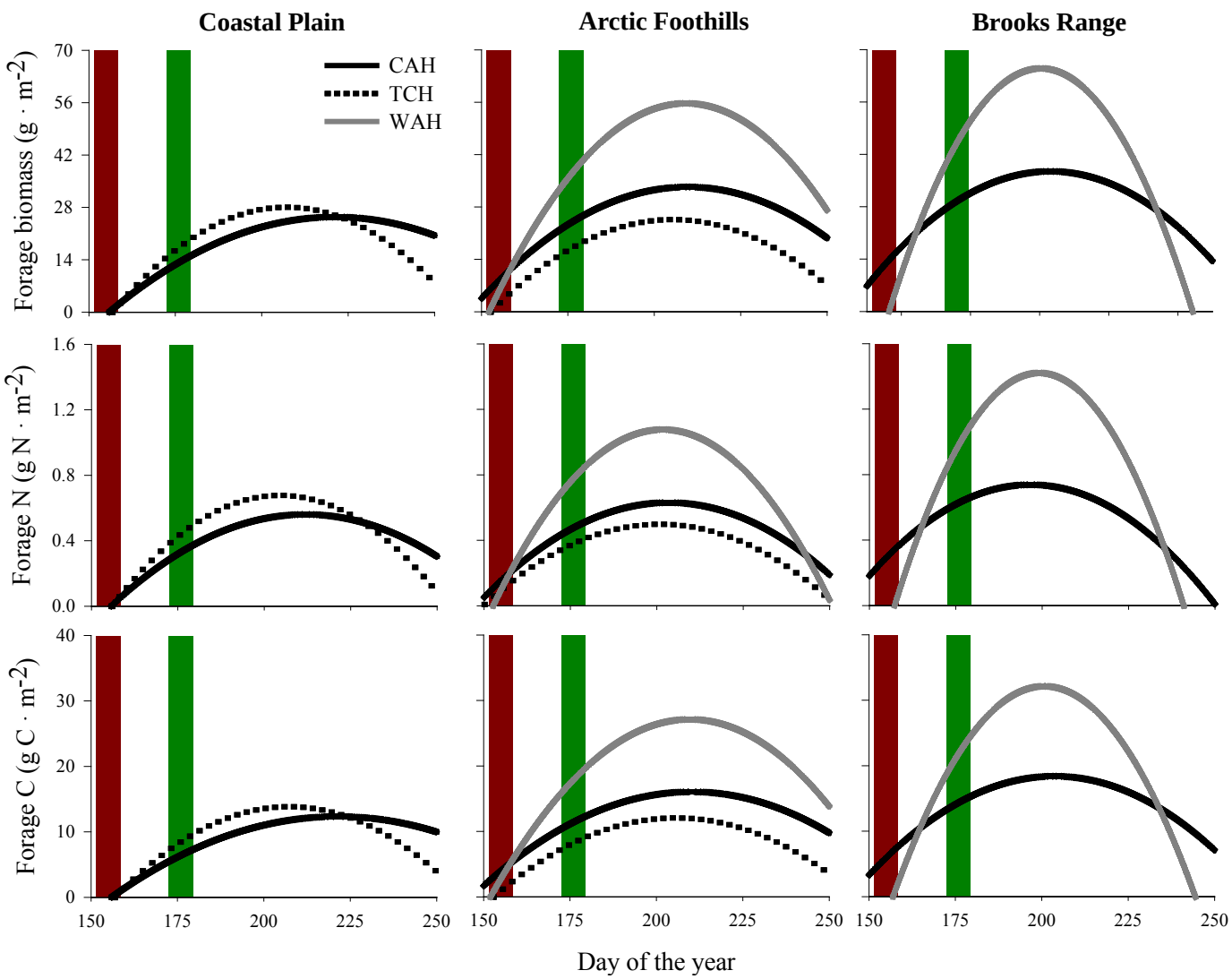

Figure 7. The average forage biomass, N, and C by day of the year at macroplots within each ecoregion (Fig. 1) for the Central Arctic (CAH), Teshekpuk (TCH), and Western Arctic (WAH) caribou herds on the North Slope of Alaska, 2011-14; peak calving and lactation are depicted by red and green bars, respectively.

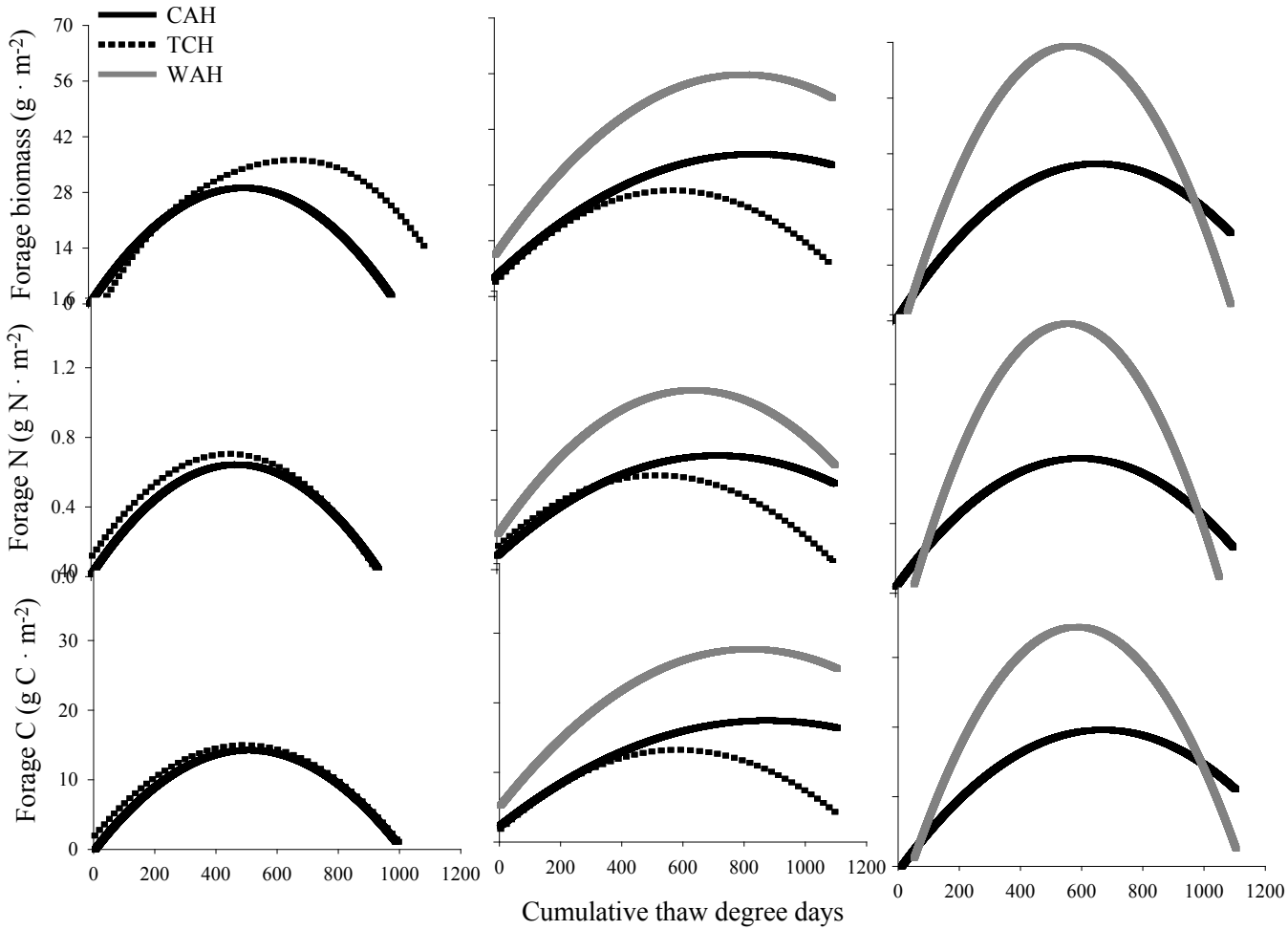

Figure 8. The average forage biomass, N, and C by "summer warmth" (as indexed by cumulative thaw degree days) at macroplots within each ecoregion (Fig. 1) for the Central Arctic (CAH), Teshekpuk (TCH), and Western Arctic (WAH) caribou herds on the North Slope of Alaska, 2011-14. For simplicity, all models were estimated throughout the same range of "summer warmth", however, levels of "summer warmth" may differ (e.g., Fig. 5, see Coastal Plain).